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Can Ultralight Sails be made from Dust?

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Advanced Propulsion Workshop

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The Rocket Equation

$V_{exhaust} = I_{sp} * g$ [d/dt(MV) = 0]

$dV = V_{exhaust} * \log(\text{final mass} / \text{initial mass})$

Material	Isp	Limitation
solid fuel	200-250	mass-starved
LH2/LOX	350-450	mass-starved
Nuclear Thermal	825-925	mass-starved
MHD	2000-5000	energy-starved
ION	3500-10000	energy-starved
Matter-Antimatter	~1,000,000	mass-starved
Photons	30,000,000-∞	both-starved

How about a fast Pluto flyby?

Voyager=16 years to Pluto. A 1.6 year trip would take dV = 5.8e12m/5e7 s ~100 km/s

Isp	M_rocket/M_payload
100,000	1.1
10,000	2.7
1,000	22,000
400	72,000,000,000

We aren't going to use chemical rockets if we want a fast Pluto flyby larger than a pencil eraser.

How do solar sails work?

Momentum of photon = E/c, if we reflect the photon, then dp = 2 E/c. At 1 AU, E_sunlight=1.4 kW/m^2==>9μN/m^2=9μPa

Then to get to Pluto in 1.6 years, we need ~0.004 m/s^2 of acceleration. To get this acceleration with sunlight we need a total mass loading of <2gm/m^2 !

- Mylar materials ~ 6 gm/m^2
- Carbon fiber mesh < 5 gm/m^2 (3/2/2000)

We are getting close!

Issues in Solar Sails

- Mass loading of reflective foils
- Albedo or reflectivity of thin foils
- Deployment of thin films
- Extra mass of booms, deployers, etc
- Survival of thin films in hostile environment of UV, flares, particle radiation, charging

"packageability, areal density, structural stability, deployability, controllability, and scalability...strength, modulus, areal density, reflectivity, emissivity, electrical conductivity, thermal tolerance, toughness, and radiation sensitivity." *Gossamer AO*

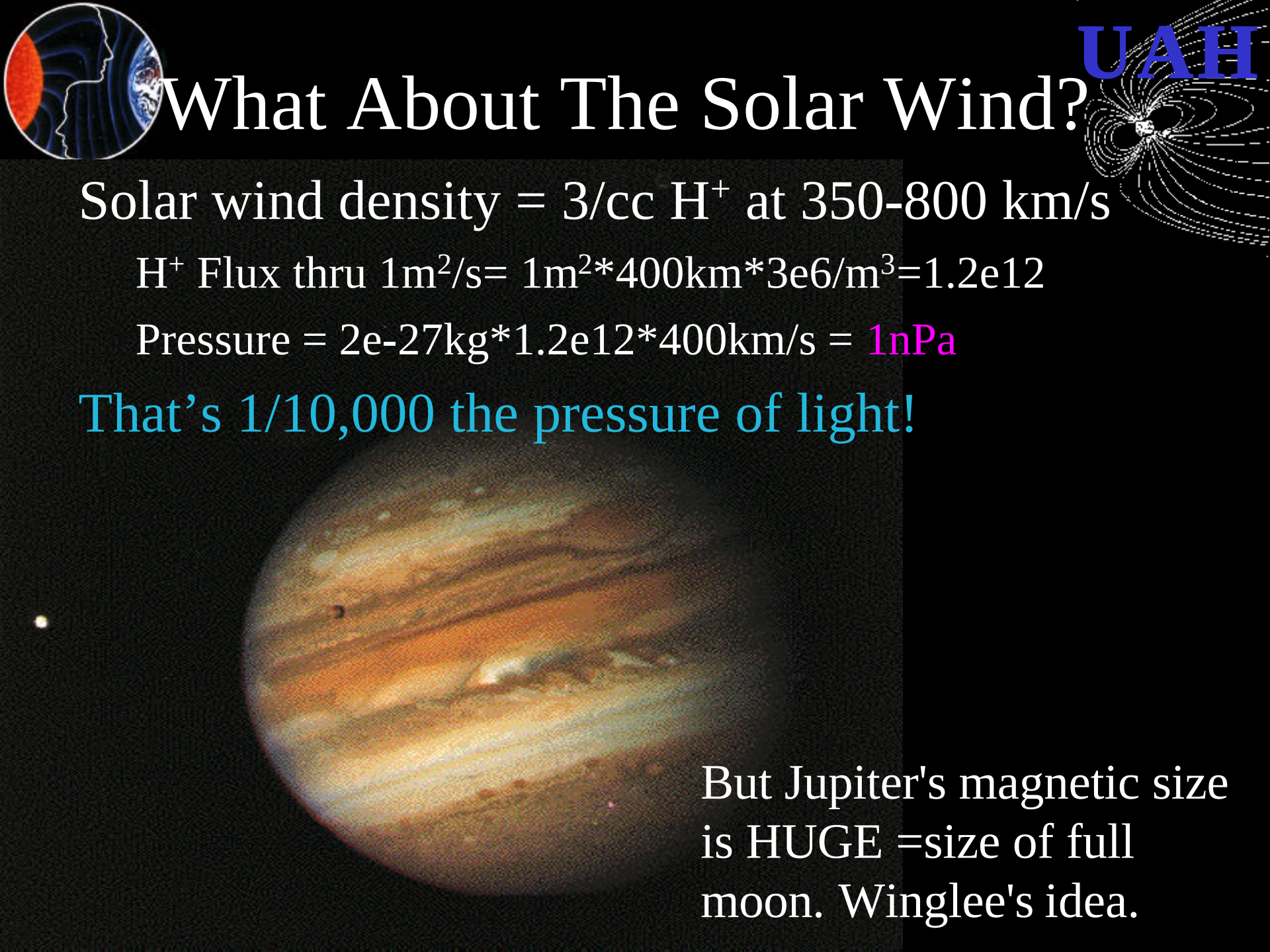
What About The Solar Wind?

Solar wind density = 3/cc H^+ at 350-800 km/s

H^+ Flux thru $1m^2/s = 1m^2*400km*3e6/m^3 = 1.2e12$

Pressure = 2e-27kg*1.2e12*400km/s = 1nPa

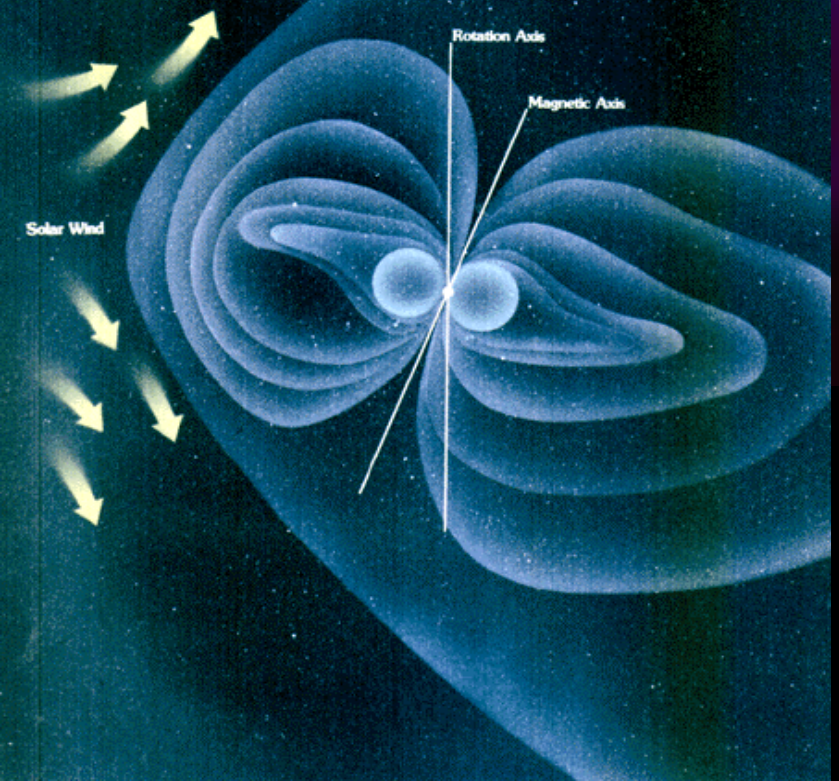
That's 1/10,000 the pressure of light!

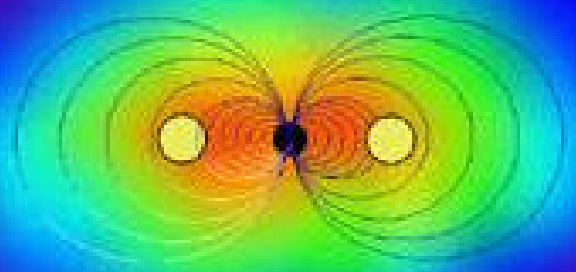


But Jupiter's magnetic size is HUGE =size of full moon. Winglee's idea.

Plasma Sail Capabilities

It isn't pressure, it's acceleration we want. A plasma sail that is lighter than a solar sail will achieve higher acceleration



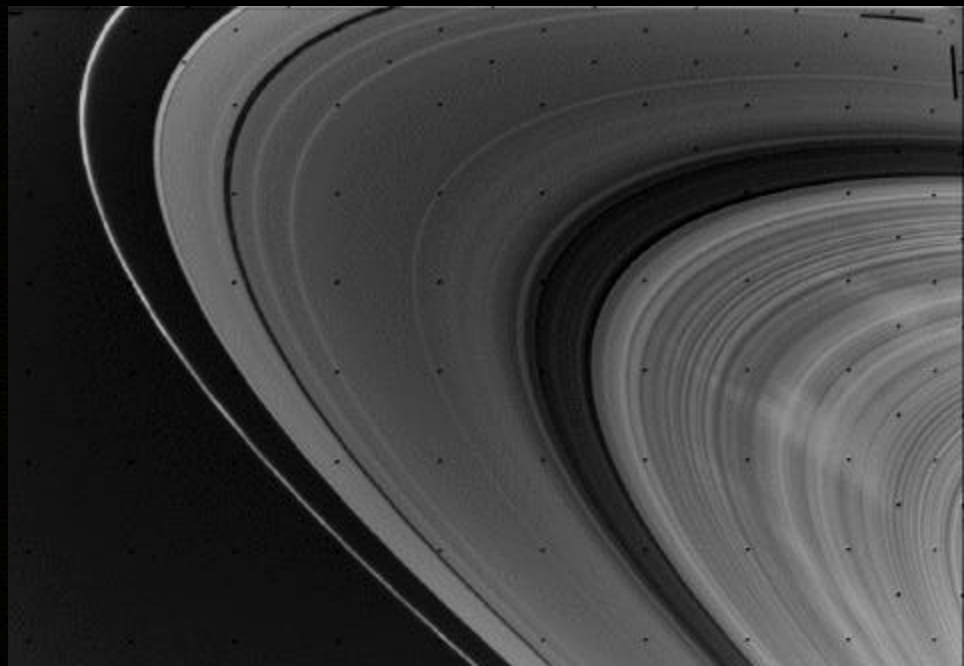


Magnetic fields don't weigh much for their size.

Trapped plasma inflates the magnetic field, e.g. Jupiter is pumped up by Io.

Robust

Dusty Plasma Sails



Hybrid Vigour

Q: Can we combine a sunlight sail having high light pressure, with a robust plasma sail (M2P2) having easy deployment?

A: Yes, by suspending opaque material in M2P2.

- For each 1% change in albedo, we increase the thrust by 50X compared to solar wind alone (at Earth orbit).
- Optically thick plasma < 1% opacity, dust is better.

Q: Can we suspend dust in a plasma sail (M2P2)?

A: Several experiments have already demonstrated the feasibility.

Hypothetical Dust Sail

Let's suppose that we find an opaque dusty plasma material for our sail that weighs the same as the propellant ~ 100 kg. Then let satellite + propellant + payload =300kg

30 km diameter with 2% opacity = 91nPa

64 N / 300 kg = 0.21 m/s^2 = 2% of g!

36 days to Mars

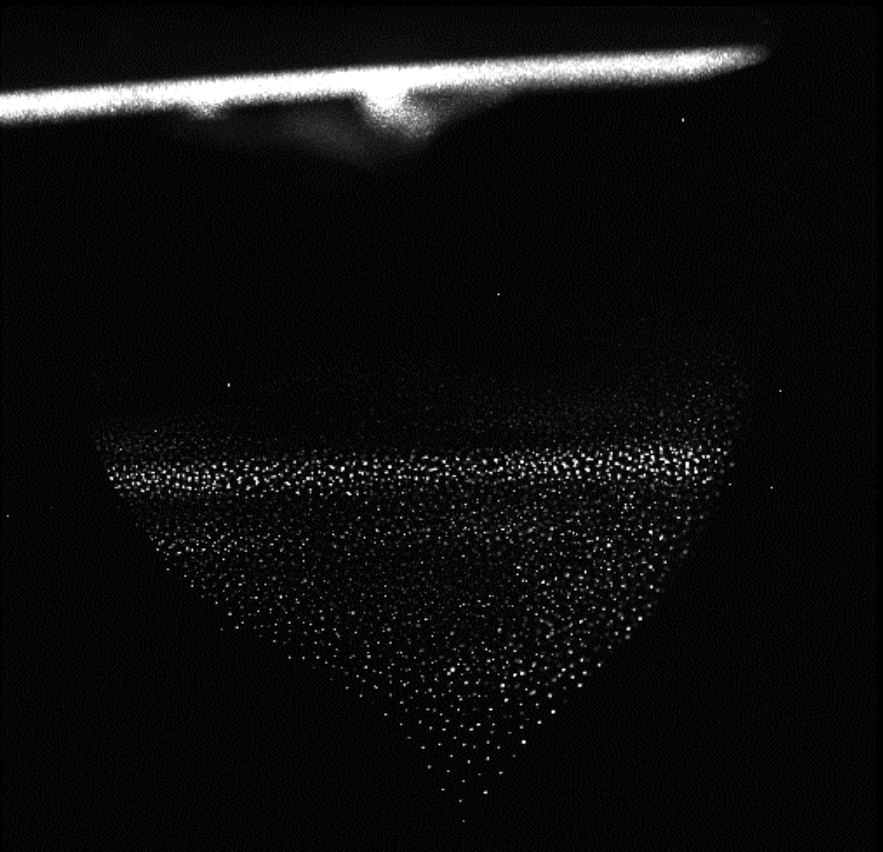
72 days to Jupiter

7.4 months to Pluto

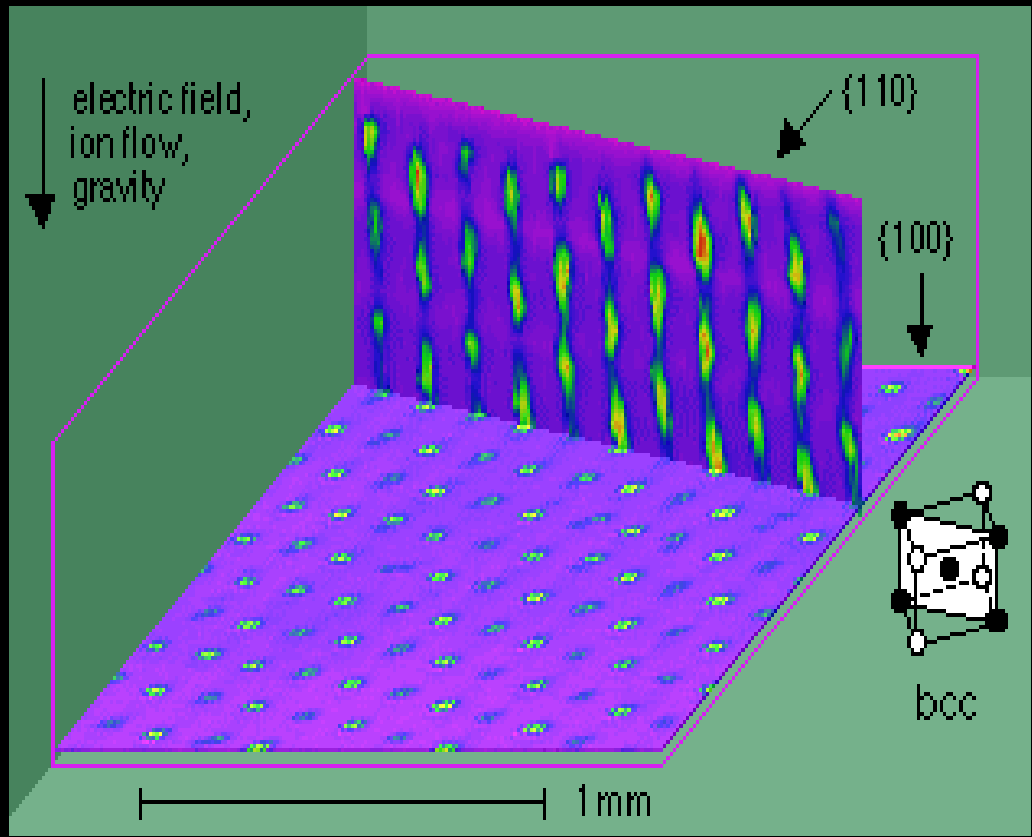
Dusty Plasmas

Charged dust, when combined with a plasma, scatters light, and can form a "Coulomb crystal"

Auburn University



University of Iowa



Scaling Up

Problem: if dust fills the volume of the plasma sail, say, like a vacuum cleaner bag, THEN the dusty sail scales up very poorly.

Mass ==> Volume, Force==>Area

Can we confine the dust to a 2-D layer and improve the scaling?

YES! Several recent papers show the way.

Magnetized, levitated dust

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Rigid and differential plasma crystal rotation induced by magnetic fields

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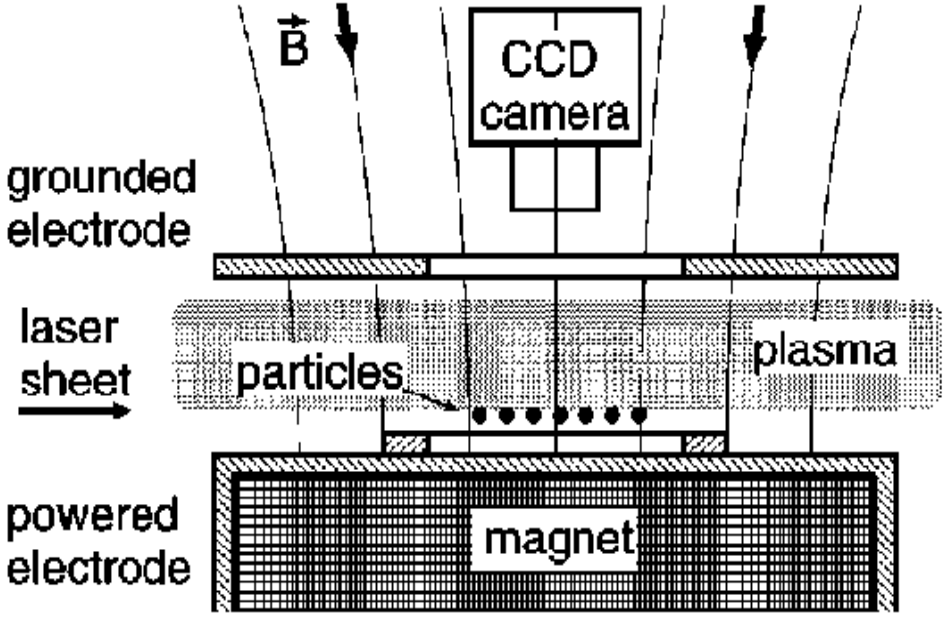
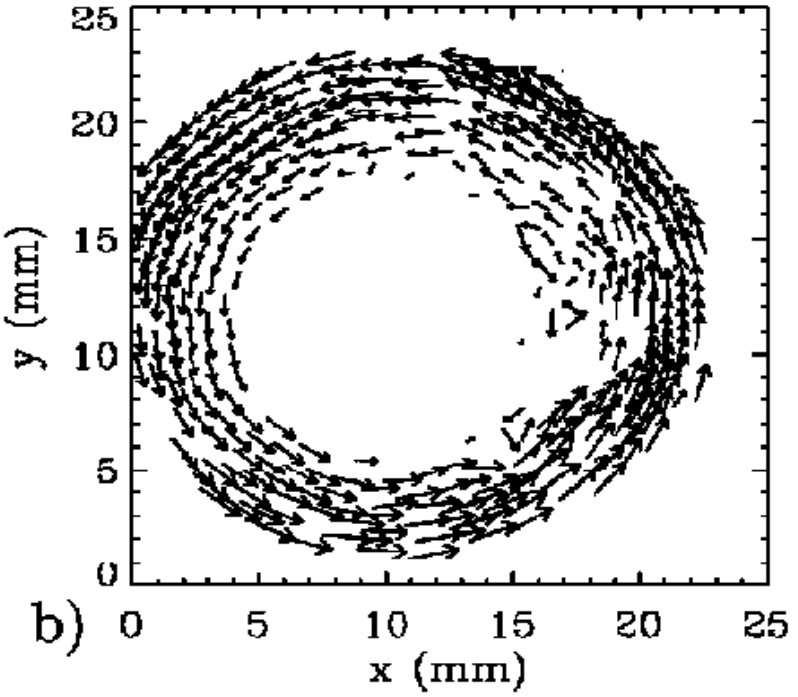
(Received 14 June 1999)



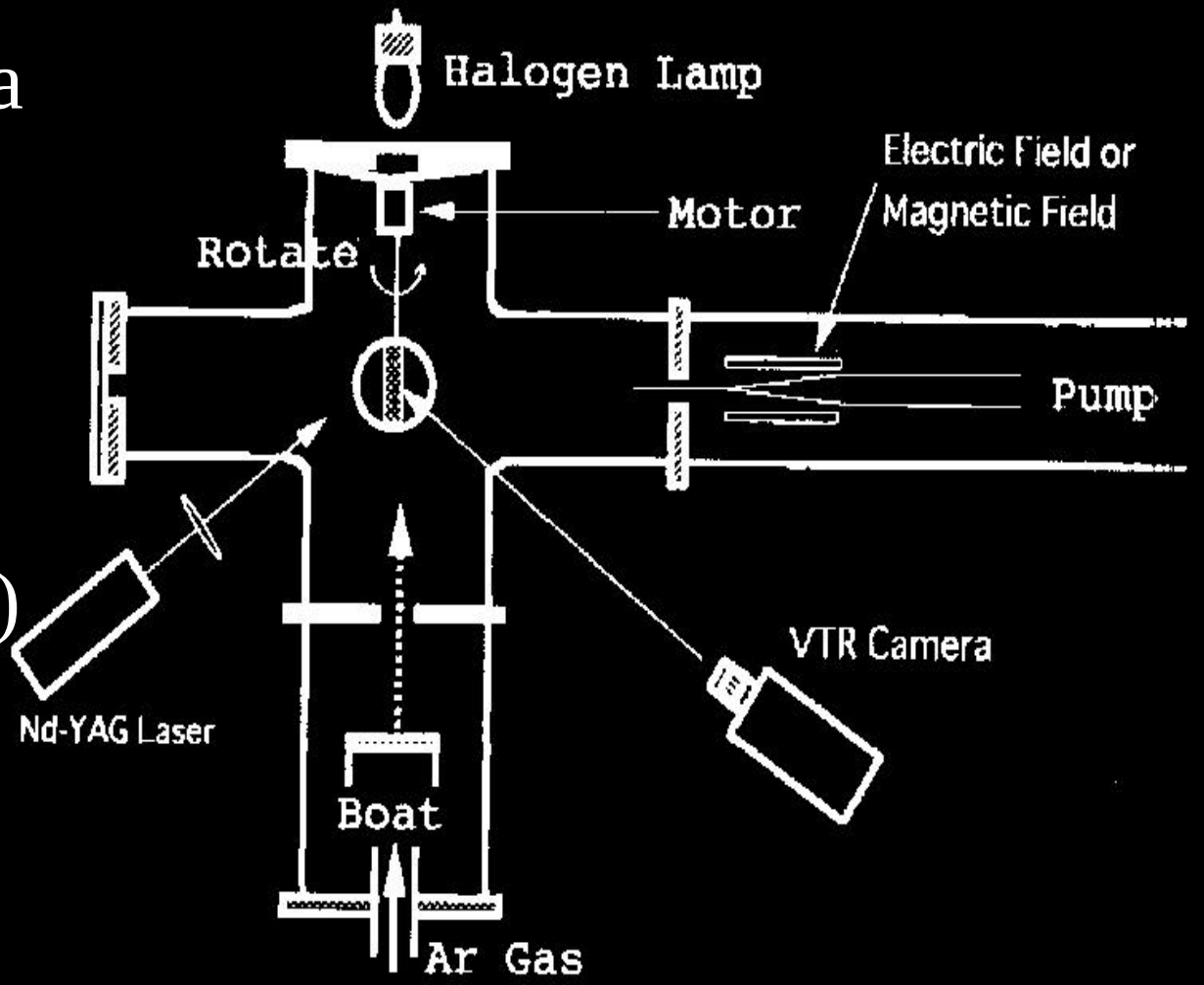


Saturn's Rings in the Lab

Charged dust is injected close to a spinning magnet

A dust ring is trapped in the vicinity of the magnet (bad fax!)

Toshiaki Yokota, Ehime Univ., April 2001.



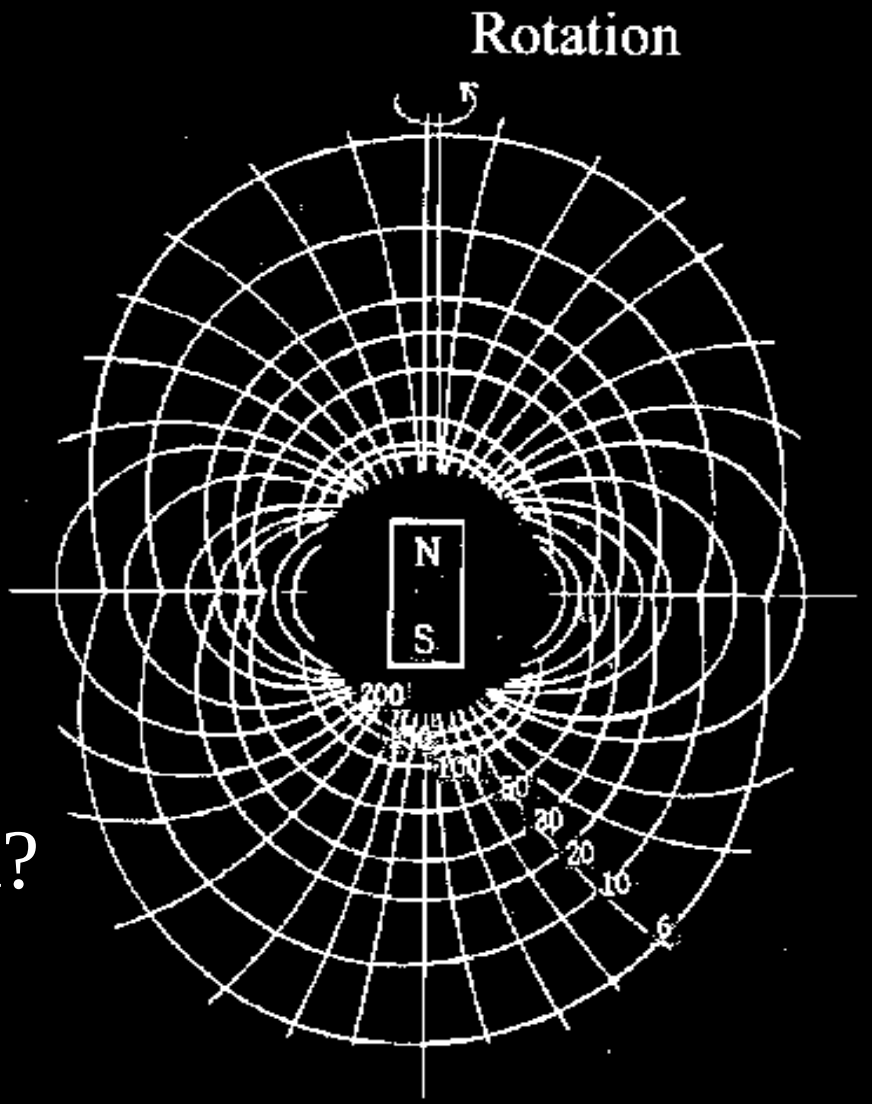
Importance of rings

Spinning the magnet produces E = v x B

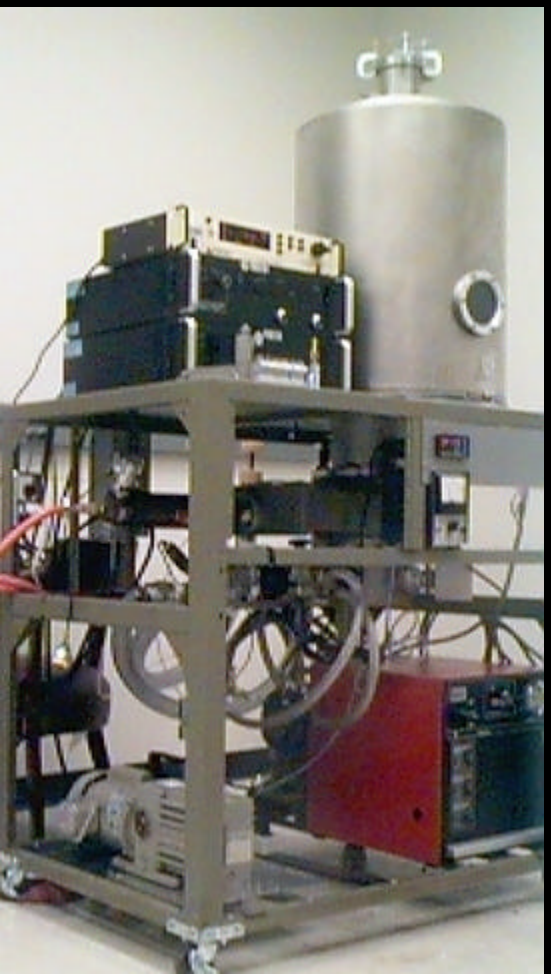
Electric forces confine dust to the equatorial plane.

Charging the magnet produces analogous behaviour (Phys.Rev).

Can we combine the two approaches to achieve both dust & plasma confinement?



UAH Spinning Terrella Experiment

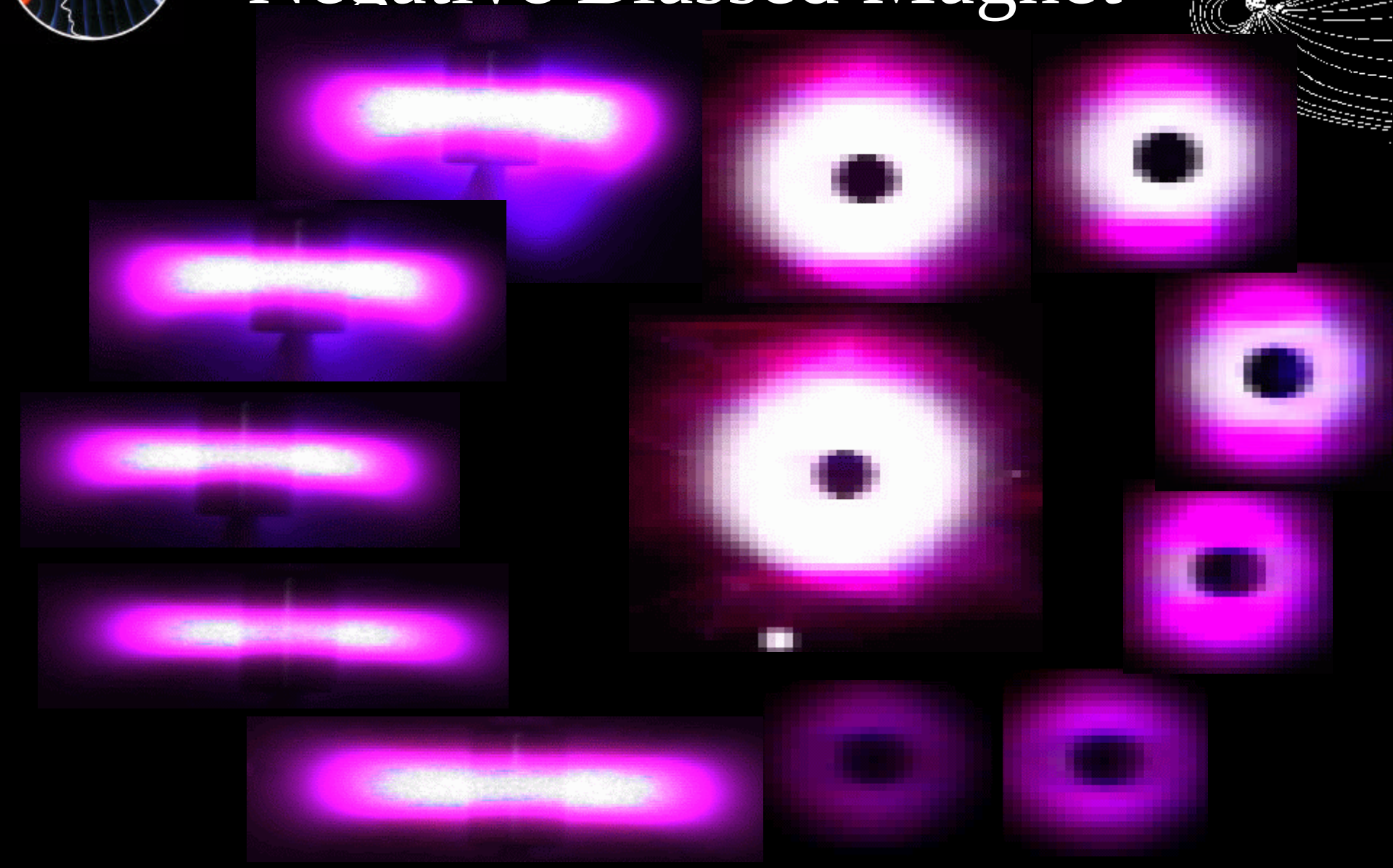


Bell jar, oil roughing pump, HV power supply, Nd-B ceramic magnet

Needle valve used to control the pressure from 10-400 mTorr

Simple

Negative Biassed Magnet



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Adding Dust?

We've discovered that levitating dust is still a black art, and we are still in the dark.

We've tried 3 micron SiO2, Xerox toner (carbon polymer) without success. Our ionization method (which others have used) was plasma arcing. However, our system runs hot, fusing the dust.

We are modifying the experiment to add a UV light source, as a gentler ionization technique.

We emphasize that our approach is unsophisticated and LOTS (Lowes-off-the-shelf). One shouldn't conclude that a better organized effort wouldn't be successful.

Future Directions

Can we make the dust lighter and more reflective? Perhaps buckeyballs with chelated sodium atoms. Or even reflective ions - e.g., transition metal ions. This is fundamental research into scattering cross sections.

Is there an optimum size dust grain? We have used 3micron SiO2, and Xerox toner. Yokota used 0.5 micron Al dust.

What are the differences between spinning the magnet and applying a potential? Is there an optimum combination?

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Conclusions

While apparently "one-way", it can be combined with gravity assist, momentum-tethers, etc to provide complete round-trip travel to the planets.

What a dusty sail lacks in efficiency, it makes up for in deployment, weight, and durability, giving a new meaning to the word "gossamer".

Dusty plasma sails may be the fastest way out of the solar system. They offer COTS technology for very fast transport.

Basic dusty plasma physics, and its interaction with a dipole magnetic field still need to be done.

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